

Polarization Alignment in JVAS/CLASS flat spectrum radio surveys

Prabhakar Tiwari and Pankaj Jain

Department of Physics, Indian Institute of Technology, Kanpur - 208016, India

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ABSTRACT

We present a detailed statistical analysis of the alignment of polarizations of radio sources at high redshift. We use the JVAS/CLASS 8.4-GHz surveys for our study. This study is motivated by the puzzling signal of alignment of polarizations from distant quasars at optical frequencies. We explore several different cuts on the polarization flux for our analysis. We find that the entire data shows a very significant signal of alignment on very large distance scales of order 500 Mpc. The alignment starts to decay only at much larger distances of order Gpc. If we only consider data with polarization flux greater than 1 mJy, we find alignment at distance scales less than 150 Mpc. We also find that data with polarization flux less than 0.5 mJy does not show significant alignment. Similar results are seen for data with degree of polarization less than 0.01, although here a mild signal of alignment is observed for a narrow range of angular separations. We argue that the signal cannot be explained in terms of bias due to systematic errors in removal of instrumental polarization. We also find that the degree of polarization shows a strong negative correlation with the total flux. The data appears to fall into two classes, one of which shows such a correlation. The remaining set, which has total flux greater than 100 mJy and degree of polarization lying between 0.01 and 0.1, shows a more random behaviour. The latter set is also found to show no alignment whereas the first set shows a very strong polarization alignment.

Key words: polarization, galaxies: high redshift, galaxies: active

1 INTRODUCTION

The Big Bang model assumes that the Universe is homogeneous and isotropic on large distance scales. However there currently exist several observations which appear to violate this basic assumption. In particular the radio polarizations from radio galaxies appear to show a large scale dipole pattern across the sky (Birch 1982; Kendall and Young 1984; Jain and Ralston 1999). The possibility that the signal observed by Birch (1982) might arise due to bias was raised in (Phinney and Webster 1983). The signal was dismissed by Bietenholz and Kronberg (1984) who found that it is not present in a larger data set. However Jain and Ralston (1999) argued that the signal is present if we consider all the radio sources for which the relevant information, i.e. the polarization position angle and the galaxy orientation angle, is available in the literature. It is also interesting that the dipole axis found in Jain and Ralston (1999) aligns closely with the Cosmic Microwave Background Radiation (CMBR) dipole axis. Furthermore a recent study finds a dipole anisotropy in the brightness of radio sources which is much larger than what is predicted by the Doppler effect due to local motion (Singal 2011). This also indicates a dipole

axis which may be of cosmological origin and well aligned with the CMBR dipole.

The optical polarizations from quasars also show alignment over cosmologically large distances (Hutsemékers et al. 1998; Hutsemékers and Lamy 2000; Jain et al. 2003). The distance scale of these correlations is of the order of Gpc (Jain et al. 2003). Furthermore the Cosmic Microwave Background Radiation (CMBR) data shows several features (de Oliveira-Costa et al. 2004; Eriksen et al. 2004; Ralston and Jain 2004; Land and Magueijo 2005; Kim and Naselsky 2010; Samal et al. 2008, 2009) which are not consistent with Big Bang cosmology. We point out that the WMAP science team has argued that some of the claimed anomalies in CMBR data set may arise due to a posteriori choice of statistics to test for a particular effect (Bennett et al. 2011). In other words one notices a particular odd feature in the data and then devises a statistic to test its significance. Such a procedure is likely to overestimate the significance of the detected anomaly. In view of this it is extremely interesting that alignment axis of CMBR quadrupole and octopole (de Oliveira-Costa et al. 2004), radio dipole axis (Jain and Ralston 1999) and the two point correla-

tions in the optical polarizations (Hutsemékers et al. 1998; Hutsemékers and Lamy 2000; Jain et al. 2003) all align very closely with the CMBR dipole axis (Ralston and Jain 2004) and point roughly in the direction of the Virgo cluster. Furthermore there has also been claims of violation of isotropy in cluster peculiar velocities (Kashlinsky et al. 2009b,a) and galaxy surveys (Itoh et al. 2010). Remarkably the cluster peculiar velocities also indicate a direction close to the CMB dipole if we include the highest redshift data. The spiral galaxies also appear to show an interesting signal of parity violation (Longo 2011). There exist many attempts to theoretically explain these observations, most of which assume violation of the cosmological principle. An interesting possibility, which is completely consistent with the Inflationary Big Bang model, is that the universe was inhomogeneous and anisotropic at very early stage, before the epoch of inflation. It evolves into a homogeneous and isotropic de-Sitter space-time during inflation. It has been shown that, for a wide class of models, there exists parameter range such that the modes generated during this early phase can re-enter the horizon much before the current era and hence can affect present observations (Aluri and Jain 2011). These can, in principle, generate the observed anisotropies.

In (Jackson et al. 2007), the authors compiled a catalogue of radio polarizations from distant radio galaxies. The catalogue contained a total of 12743 sources. Motivated by the observed linear polarization alignment in quasar data (Hutsemékers et al. 1998; Hutsemékers and Lamy 2000) at visible wavelengths, Joshi et al. (2007) studied the possibility of a similar effect at radio frequencies using this catalogue. No significant effect was detected. The alignment in optical polarizations is seen over cosmologically large distances of order Gpc (Hutsemékers et al. 1998; Hutsemékers and Lamy 2000; Jain et al. 2003). and the phenomena is very puzzling. There are several possible models (Hutsemékers et al. 1998; Hutsemékers and Lamy 2000; Jain et al. 2002; Hutsemékers et al. 2005; Payez et al. 2008; Piotrovich et al. 2008; Urban and Zhitnitsky 2011; Ciarcelluti 2012) looking for the interpretation of this alignment. One possibility is that this alignment arises due to large scale correlations in the intergalactic magnetic field (Agarwal et al. 2008). The intergalactic magnetic field may be seeded in the early Universe (Subramanian and Seshadri 2003; Seshadri and Subramanian 2005, 2009) and presence of large scale correlations in this field are not necessarily in conflict with the Big Bang cosmological model (Agarwal et al. 2008). We still require a mechanism for how such a magnetic field generates large scale correlations in the optical polarizations. One possibility is that this is caused by mixing of photons with hypothetical pseudoscalars (Jain et al. 2002; Hutsemékers et al. 2005; Payez et al. 2008; Piotrovich et al. 2008; Agarwal et al. 2008). This effect is frequency dependent and is much smaller at radio frequencies (Jain et al. 2002). Hence it may be consistent with absence or reduced alignment effect in radio polarizations. There have also been other proposals to explain this effect (Urban and Zhitnitsky 2011; Ciarcelluti 2012).

In the present paper we analyze the radio data in order to study possible alignment of radio polarizations. A study of radio polarizations to check for alignment was earlier conducted in (Joshi et al. 2007). Here we extend this work by considering the fact that polarization angles de-

pend on the coordinate system used. In order to properly analyze the presence or absence of large scale alignment one needs to define a coordinate invariant statistics (Jain et al. 2003). The basic point is that, in order to compare two polarization angles on the surface of the celestial sphere, one needs to parallel transport one of them to the position of the second along the great circle joining the two points. The contribution due to parallel transport may be negligible in most cases, if the two points are separated by a small distance. However it becomes very important if we are testing alignment over large distances. Furthermore in (Joshi et al. 2007), the authors restricted their analysis to data which has polarization flux density greater than 1 mJy. Here we also analyze data with lower polarization flux density.

The data at low polarization flux density might be more contaminated with noise. However this will not affect our alignment results unless there is significant bias in the data. A potential source of bias is the error in the removal of residual instrumental polarization (Jackson et al. 2007; Joshi et al. 2007). This can lead to large scale correlations in polarizations even when none are present. It is clear that this effect will dominate for sources which have low degree of polarization and/or low polarization flux. Hence one can evaluate its contribution by focussing on data with low polarization. Another source of error is the positive bias (Simmons and Stewart 1984; Jackson et al. 2007) that arises in the degree of polarization. This arises since the degree of polarization depends on the squares of Q and U and will always acquire a positive value. However this cannot affect the alignment statistics which are based only on the linear polarization angle. Furthermore we point out that there is some motivation for looking at alignment at lower polarizations since some theoretical models (Das et al. 2005, 2008; Agarwal et al. 2008) predict a smaller polarization for radio frequencies. Hence here we might expect alignment only at smaller polarization. We also point out that the entire field of Cosmic Microwave Background Radiation polarization is based on polarization flux which is of order 10^{-6} in comparison to the total intensity (see, for example, Weinberg 2008). This is much smaller than the degree of polarization of the radio data we consider here. Hence we do not see any reason to discard data with smaller polarization flux. In any case one should be cautious in interpreting our results for low polarizations.

We also point out that errors in polarization position angle (PA) calibration can also reduce the true significance of alignment that might be present in data. This will lead to a systematic error in the observed PA. This can mask an alignment effect present in data since this systematic error may be different in different runs (Joshi et al. 2007).

2 DATA SELECTION

In our study we use the data available in the catalogue produced by Jackson et al. (2007). It contains a total of 12743 radio sources and lists the angular positions and the Stokes I , Q and U parameters. Since the redshift of most of these sources is unknown, we assume that these sources are roughly at the same redshift equal to unity. The input observable for the alignment study is the polarization PA.

The calibration methods and the catalogue production has been discussed in detail in Jackson et al. (2007).

3 STATISTICAL PROCEDURE

All astronomical observations are made on the hypothetical celestial sphere and any directional measurement on this sphere correspond to a particular coordinate system. For example, the polarization angles are measured in a local frame, formed by two unit vectors $\hat{\phi}$ and $\hat{\theta}$. These unit vectors depends on the coordinate system used, i.e. they depend on which direction we choose as our North Pole, and hence one cannot directly compare vectors at different positions on the celestial sphere. The proper procedure to compare such vectors is to transport one of them to the position of the second along the geodesic joining the two positions. A detailed procedure has been discussed in Jain et al. (2003) and we follow this procedure for comparing polarization angles of two different sources.

We define a statistic S_D to quantify the alignment (Hutsemékers et al. 1998; Jain et al. 2003). Let us suppose we want to calculate the alignment of the polarization at a site k with its n_v nearest neighbours. We first need to parallel transport the polarization angles from each site to the site k and then we compare all polarization angles with polarization at the k^{th} site. We define a measure of dispersion, d_k , at site k as

$$d_k = \frac{1}{n_v} \sum_{i=1}^{n_v} \cos[2(\psi_i + \Delta_{i \rightarrow k}) - 2\psi_k]. \quad (1)$$

Here ψ_i are the polarization angles of the nearest neighbours of the k^{th} site and the factor $\Delta_{i \rightarrow k}$ arises due to parallel transport from $i \rightarrow k$. The sum in Eq. 1 includes the site k also. We next maximize d_k as a function of ψ_k . The resulting value of ψ_k is interpreted as the mean polarization angle at the site k and the corresponding maxima of the function in Eq. 1 gives an estimate of d_k . The statistic may now be defined as (Hutsemékers et al. 1998; Jain et al. 2003),

$$S_D = \frac{1}{n_s} \sum_{k=1}^{n_s} d_k \Big|_{\max}, \quad (2)$$

where n_s is the total number of samples in the data. A large value of S_D indicates a strong alignment between polarization vectors.

In this paper we use the statistic defined in Eq. 2 to determine whether the radio polarization data shows significant alignment. In (Joshi et al. 2007) the authors imposed a cut on polarization flux density to include only sources with polarization flux greater than 1 mJy. As we discuss in the Introduction we study alignment both with and without this cut. The data set contains a total of 4400 sources with polarization flux > 1 mJy and 7452 sources with polarization flux > 0.5 mJy. The number of sources with polarization flux lying between 0.5 mJy and 1 mJy is 3051. The total number of sources without any cut is 12743. We note that the sources lie dominantly in the Northern hemisphere. Furthermore there are very few sources along the galactic plane.

The significance of alignment in the data set is computed as follows. We first compute the statistics defined in Eq. 2 for a given number of nearest neighbours of any source.

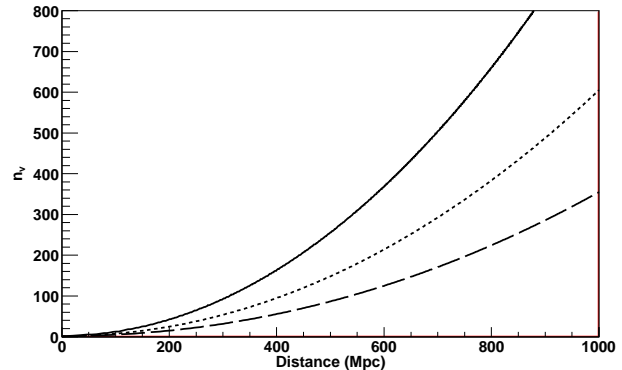


Figure 1. The mean distance (Mpc) among sources as a function of the number of nearest neighbours (n_v) for the full data set (solid line), set with polarization flux greater than 0.5 (short dashed line) and with polarization flux greater than 1 (long dashed line).

This statistic is compared with the result for a large number of random samples, which are generated by shuffling all the PAs among different sources. In our simulations we use a total of 1000 random samples for a given number of nearest neighbours. The probability that the alignment seen in data might arise as a random fluctuation is determined by the number of random samples which shows a larger value of statistic in comparison to the real data. If we find that none of the random samples shows a larger value of the statistic then the significance is computed by determining the mean and standard deviation of the random set and assuming that the distribution of random samples is approximately Gaussian.

The number of nearest neighbours n_v of any source are computed by assuming that all the sources are located at the same redshift of 1.0. The redshift information of these sources is not currently available and hence we make this assumption. Essentially here we are ignoring the third dimension and determining the nearest neighbours only on the basis of the angular separations. It is likely that in many cases this will lead to a wrong assignment of the set of nearest neighbours of a source. However this also cannot generate alignment in a data set if none is present. If the data does show alignment at any distance scale then it will affect the detailed numerical results. For example, let us assume that the radio polarizations are aligned over a small distance scale of a few Mpc, but show no alignment over larger distances. Our nearest neighbour assignment may include some sources which are in fact much further away. It is clear that these sources which are mis-identified as nearest neighbours will only add noise to the signal and reduce the significance of alignment. In Fig. 1, we show the relationship between the number of nearest neighbours and the mean comoving distance from a source within which these nearest neighbours reside. Here the mean is taken over the entire sample. We have assumed that all sources are located at a redshift of 1. Furthermore we assume the standard Lambda Cold Dark Matter model for computing the comoving distance (see, for example, Weinberg 2008).

The distribution of statistics for random sample is shown in Fig. 2 for the number of nearest neighbours $n_v = 10$ and 50. Here we use 1000 random samples generated by ran-

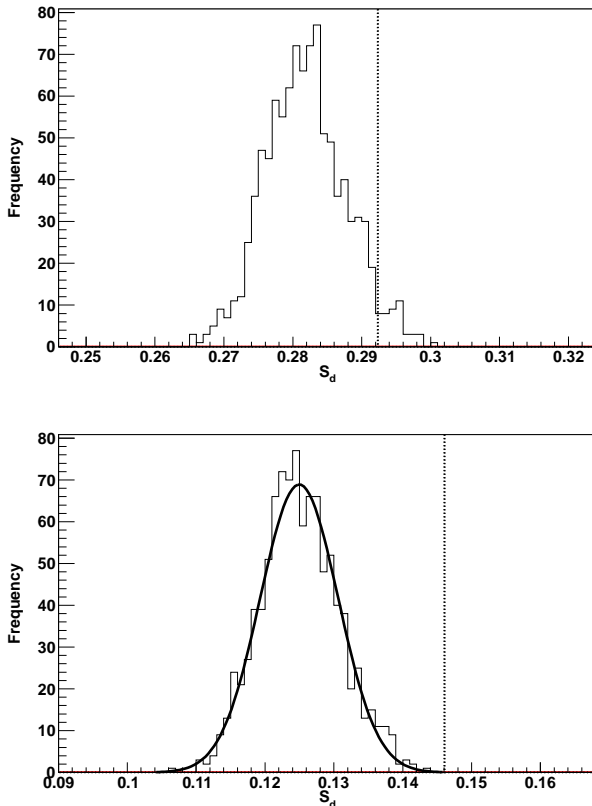


Figure 2. The statistic S_D histogram for the shuffled PA,s for 10 and 50 nearest neighbours. The plot shows distribution of 1000 random samples generated by randomly shuffling data for radio sources with polarization flux lying between 0.5 and 1.0 mJy. For the case of 50 nearest neighbours, we also show a Gaussian fit to the distribution. The vertical line in each plot shows the corresponding value of S_D for the actual data.

domly shuffling data for radio sources with polarization flux lying between 0.5 and 1.0 mJy. For the case of 50 nearest neighbours we also show the Gaussian fit to the distribution. We find that it provides a good fit to the data. Similar distributions are seen for all the values of n_v and the cuts on polarization flux used in this paper. In all these cases we find that the Gaussian provides a good fit to the data.

4 RESULTS

In Fig. 3 we show the results for polarization flux density greater than one. The upper graph shows the statistic S_D as a function of the number of nearest neighbours. The dots denote the values of the statistic for the data sample. We also show the results obtained from the random samples generated by shuffling polarizations among different sources. We show the mean and standard deviation of the random samples. The significance of alignment of this data set is shown in the lower graph. Here we show the significance in terms of the sigma values by which the data differs from random simulations. The corresponding results for polarization flux density lying between 0.5 mJy and 1 mJy are shown in Fig. 4.

For polarization flux greater than unity we do not find

a significant alignment for number of nearest neighbours $n_v > 14$. This is in agreement with the results obtained in (Joshi et al. 2007). However we find significant alignment for $n_v \leq 14$. In (Joshi et al. 2007) this region was never explored. The significance of alignment is found to be more than 3 sigmas for $n_v \leq 10$. The mean comoving distance among sources for 10 nearest neighbours is about 150 Mpc. Here we compute the mean distance among nearest neighbours by assuming that all the sources are located at redshift $z = 1$ and assuming the standard Lambda Cold Dark Matter model (see, for example, Weinberg 2008). Our results show that for polarization flux greater than 1 mJy, the radio sources show alignment over distance scale of order 150 Mpc.

For polarization flux between 0.5 mJy and 1.0 mJy, we find a significant signal of alignment for number of nearest neighbours greater than 15. The significance is found to be greater than 3 sigmas for $n_v > 30$. Hence, in contrast to the data with polarization flux greater than 1.0 mJy, here we find significant correlations between sources located at large distances from one another. We have tested this for maximum value of $n_v = 100$, where we find a significance of 3 sigmas. For the entire data sample with polarization flux larger than 0.5 mJy we find significant alignment over the entire range of n_v . At $n_v = 2$ the significance is found at 2 sigma level. For all other values of n_v the significance is comparable or better than 3 sigmas. The distance scale corresponding to $n_v = 100$ is roughly 400 Mpc in this case.

In Fig. 5 we present results for the entire sample of 12743 sources without imposing any cut. Here we again find a statistically significant result for very wide range of values of n_v . The significance is better than 3 sigmas for the range $10 \leq n_v \leq 50$. Beyond this range it rises beyond 4 sigmas. In the range $150 \leq n_v \leq 350$ we find a signal more significant than 5 sigmas. Hence we see a striking signal of alignment over very large distances, of order 500 Mpc, in the entire data sample. The signal approaches 2 sigma limit only for distances close to a Gpc. In Fig. 6 we show the distribution of the statistic S_D for the entire data set for $n_v = 250$. The statistic for the observed data is also shown.

It is also useful to consider the sources which have polarization flux less than or equal to 0.5 mJy. A total of 5291 sources remain after this cut. The significance of alignment as a function of the number of nearest neighbours, n_v , is shown in Fig. 7. Here we find that sources do not show significant alignment over the entire range of values of n_v shown in Fig. 7. We also probed larger values of n_v , up to $n_v = 200$. The significance continues to remain less than 2 sigmas.

We next consider cuts based on the degree of polarization. We expect that the data with low degree of polarization would behave the same as the data with low polarization flux. However the cut based on degree of polarization is not entirely the same as that based on polarization flux. In Fig. 8 we show a plot of the total flux as a function of the degree of polarization. We notice that the two show a strong negative correlation. The Pearson's correlation coefficient between the $\log(\text{Flux})$ and $\log(\text{degree of polarization})$ is found to be $r = -0.387$. This correlation might be interesting in itself. We also note that the data seems to fall into two classes. One shows a clear negative correlation. The second with total flux greater than 100 mJy and degree of

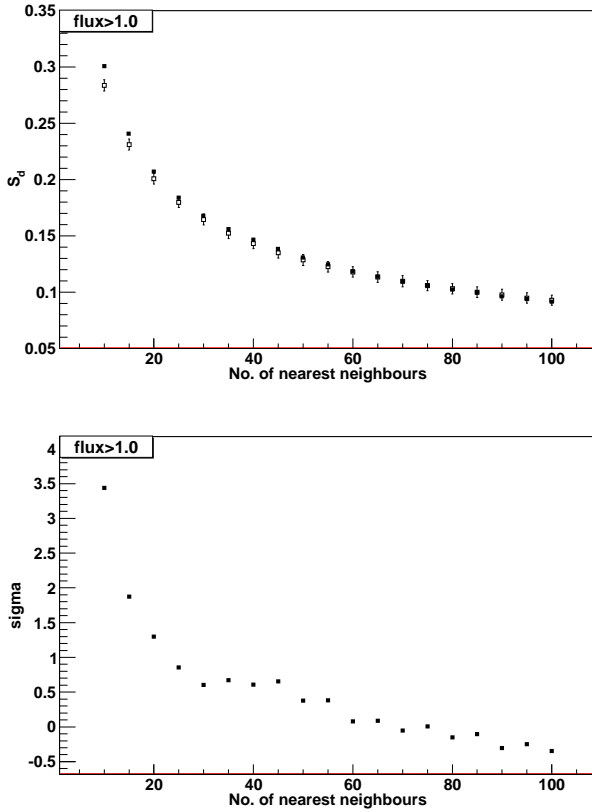


Figure 3. The statistic S_D as a function of the number of nearest neighbours, n_v , for the observed PAs and shuffled PAs for polarization flux greater than 1 mJy (upper graph). The dots denote the value corresponding to real data. The points with error bars denote the mean value of the random samples along with the standard deviation. For larger n_v the dots are not visible since they merge with the error bars. The lower graph shows the corresponding sigma values, i.e. the significance of alignment.

polarization lying between 0.01 and 0.1 showing a different behaviour. The degree of polarization is the ratio of the polarization flux and the total flux. If the polarization flux is uncorrelated with total flux, then the degree of polarization would decay like the inverse of the total flux. The data shows a weaker decay indicating a positive correlation of the polarization flux with total flux.

We next consider alignment of sources with polarization flux less than or equal to 0.01 and those with degree of polarization greater than 0.01. For comparison all the sources considered in the optical study (Hutsemékers et al. 1998; Hutsemékers and Lamy 2000) have degree of polarization greater than 0.006. The total number of sources which remain after this cut is 3441. We also consider the remaining sources with degree of polarization greater than 0.01. The significance of alignment with these two cuts is shown in Fig. 9. Here we find that the data with low degree of polarization shows a relatively weak signal for $n_v = 10, 20$ and 30. For larger n_v the significance is below 2 sigmas. In contrast the data with large degree of polarization shows a much stronger signal for $n_v \geq 40$. Hence we find that sources with low polarization flux or low degree of polarization either do not show significant alignment or show a very weak

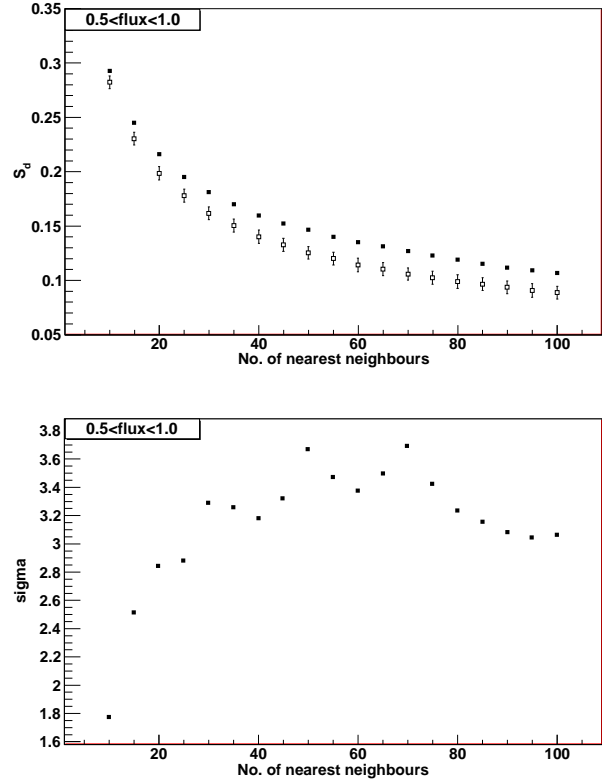


Figure 4. The statistic S_D as a function of the number of nearest neighbours, n_v , for the observed PAs and shuffled PAs for polarization flux lying between 0.5 mJy and 1 mJy (upper graph). The dots denote the value corresponding to real data. The points with error bars denote the mean value of the random samples along with the standard deviation. The lower graph shows the corresponding sigma values, i.e. the significance of alignment.

signal. The sources with degree of polarization greater than 0.01 show a strong correlation similar to the one seen in data with polarization flux greater than 0.5 mJy.

We have pointed out above that the data appears to fall into two classes, based on the correlation of the degree of polarization with the total flux (Fig. 8). We find that these two classes show very different alignment statistics. The data with total flux greater than 100 mJy and degree of polarization lying between 0.01 and 0.1 shows no alignment. The remaining data, for which the degree of polarization shows a strong (negative) correlation with total flux, shows a very strong signal of alignment. There are a total of 10983 sources in this category. The significance of alignment for this set is shown in Fig. 10. The sigma value in this case is found to be almost 6 for $n_v = 150$.

We emphasize that one should be cautious in interpreting our results for the data sample which includes the sources with low polarization flux. The fact that the sample with polarization flux less than 0.5 mJy does not show a significant signal of alignment gives us some confidence that the signal cannot be attributed to bias. In any case our results provide a very strong motivation to make further observations at higher precision to further test the signal of alignment.

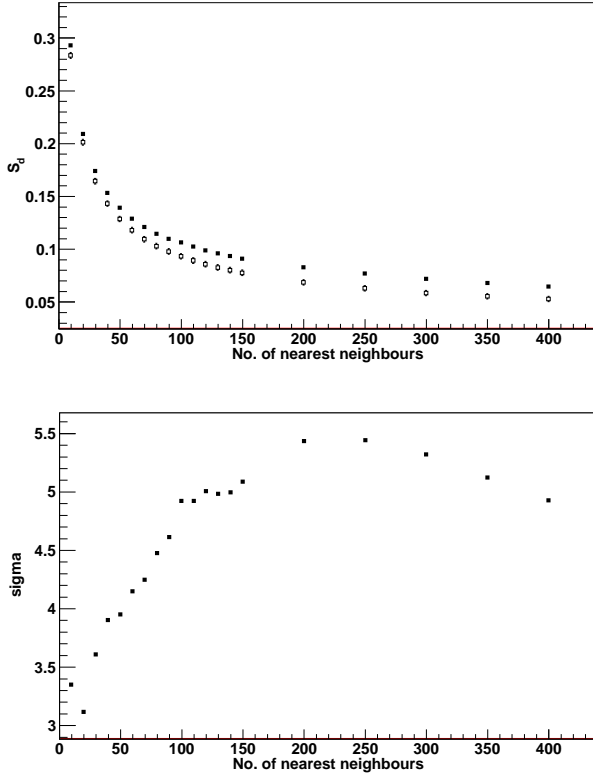


Figure 5. The statistic S_D (upper graph) and the significance (lower graph) as a function of the number of nearest neighbours n_v for the entire data sample of 12743 sources without imposing any cut on the polarization flux.

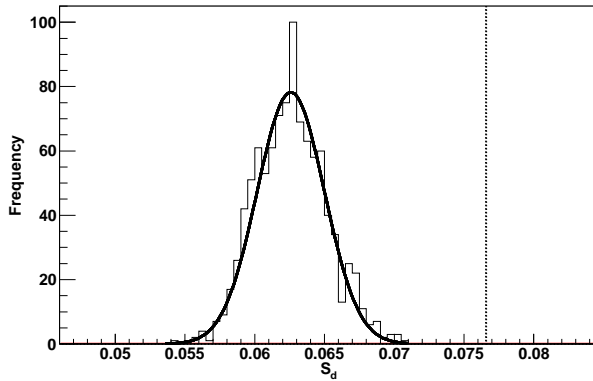


Figure 6. The distribution of statistic S_D , along with a Gaussian fit, for the complete data set for the number of nearest neighbours $n_v = 250$. The statistic for the observed data, $S_D = 0.0766$ is also shown for comparison.

5 BIAS

The fact that low polarizations show very weak alignment is very interesting since it strongly disfavors an explanation in terms of instrumental bias. If this bias is the source of the strong alignment seen in the complete data set, then the sources with low polarizations should have shown maximal effect. This is because incorrect removal of instrumental polarization adds a systematic small polarization to all the sources observed in a particular run. For sources with large

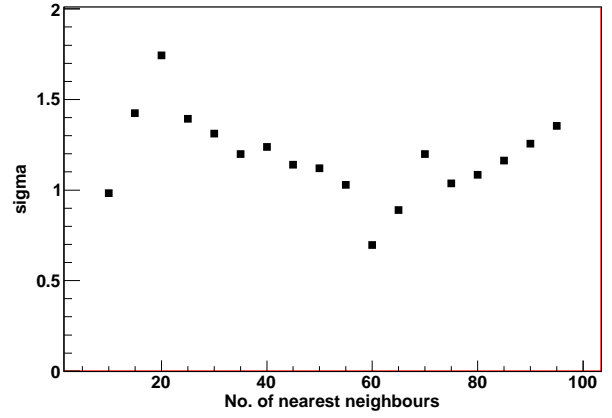


Figure 7. The significance of alignment for data with polarization flux less than or equal to 0.5 mJy as a function of the number of nearest neighbours n_v .

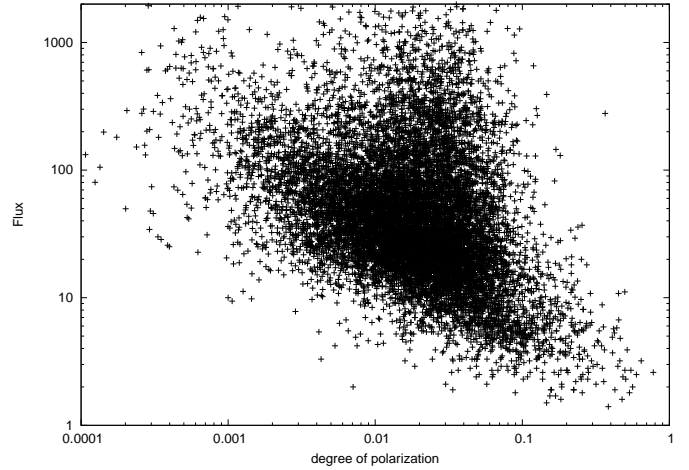


Figure 8. The total flux (in mJy) as a function of the degree of polarization.

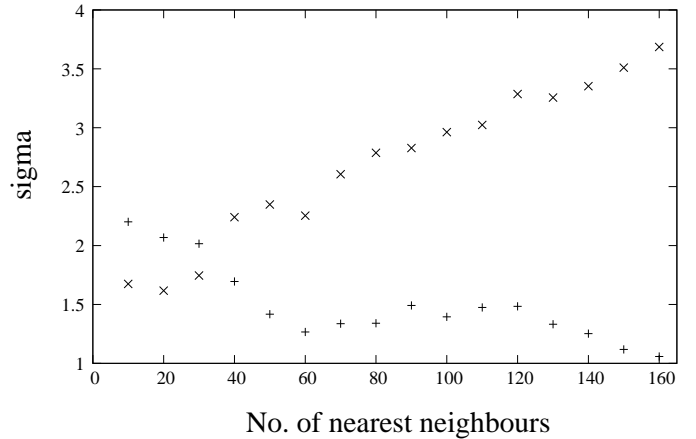


Figure 9. The significance of alignment for data with degree of polarization less than or equal to 0.01 (plusses) and for degree of polarization greater than 0.01 (crosses) as a function of the number of nearest neighbours n_v .

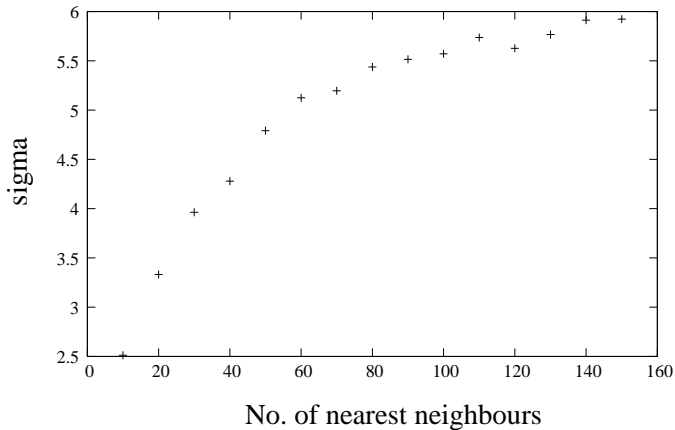


Figure 10. The significance of alignment for data with total flux less than 100 mJy or degree of polarization less than 0.01. As seen in Fig. 8, this data set shows a strong negative correlation between total flux and degree of polarization.

polarization flux, this will induce a negligible shift in the polarization angle. However the polarization angle of sources with low polarization flux will be dominated by this systematic effect. Hence we conclude that the effect cannot be attributed to instrumental noise and has a physical origin.

We point out that a bias can generate the alignment signal that we observe only if it contributes differently to different regions of the sky. If the entire data contains exactly the same bias in the polarization angle, then that bias cannot yield the alignment signal we observe. This is because, in all cases, we compute the statistical significance by shuffling the polarization angle among different sources. Hence in this case the bias will affect the random samples as much as it affects the real data.

We also perform an explicit simulation to determine how the instrumental bias might affect the observed signal of alignment. As we have argued above such a bias will dominantly affect the sources with low polarization. Hence we expect the signal to be much stronger for the data set with small polarizations in comparison to the complete set. We test this explicitly by a simulation. For this purpose we use all the sources in the same positions as the original data set. The polarization angles and other observables such as intensity, Q and U Stokes parameters are randomized by permuting them among the different sources. We consider four regions in the sky where the data has instrumental bias. These four regions are chosen as (i) $0 \leq RA \leq 6$, $Dec \leq 30^\circ$, (ii) $0 \leq RA \leq 6$, $Dec > 30^\circ$, (iii) $10 \leq RA \leq 16$, $Dec \leq 30^\circ$, (iv) $10 \leq RA \leq 16$, $Dec > 30^\circ$. Here all the RA values are specified in hours. We next induce an instrumental bias in this data set by adding a flux of 0.1 mJy to the Q and U parameters in regions (i) and (iii) respectively. We also subtract a flux of 0.1 mJy to the Q and U parameters in regions (ii) and (iv) respectively. This mocks the real data which is potentially biased due to incorrect removal of instrumental polarizations which is expected to be different at different epochs of observation. The biased data is then tested for alignment.

After inducing the bias the total number of sources with polarization flux less than or equal to 0.5 mJy is 5247. The number of sources having polarization flux between 0.5 mJy and 1 mJy are 3091. The significance of alignment for the

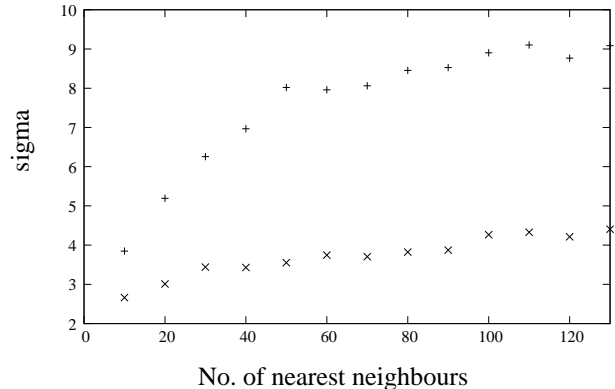


Figure 11. The significance of alignment for the simulated data. Here we induce an instrumental bias in the data set, as explained in text. The upper points (plusses) correspond to the data with polarization flux less than or equal to 0.5 mJy. The lower points (crosses) correspond to data with polarization flux lying between 0.5 mJy and 1 mJy.

simulated data is shown in Fig. 11. We find that the sources with polarization flux less than 0.5 mJy show a very strong signal of alignment. The maximum sigma value in this case is found to be about 9. In contrast the data set with polarization flux lying between 0.5 mJy and 1 mJy shows a relatively weak signal. This is clearly in contrast to what we observe in the real data. Hence we conclude that the alignment seen in real data cannot be attributed to instrumental bias. It is most likely caused by a physical phenomenon, with the low polarization sample primarily dominated by noise.

We have also explicitly verified by simulations that if all the data points contain the same instrumental error throughout the sky then we do not obtain any significant alignment. In this case we find that although the statistic S_D is large for the biased data sample, it is also large for the random samples generated by shuffling the PAs among the different sources. Hence it does not lead to any signal.

We next address the issue of bias raised in (Battye et al. 2008). The authors found a significant bias present in the polarization angles in the NVSS survey. It was found that the polarization angles have a tendency to be close to multiples of 45° . In order to study the existence of such a bias in the present data, we plot the distribution of polarization position angles in Fig. 12. Here we show the distribution for the complete set, the set with polarization flux smaller than 1 mJy and the set with polarization flux larger than 1 mJy. We find no evidence for such a bias in the present data.

Finally we study the signal seen in the sample with polarization flux greater than 1 mJy for small number of nearest neighbours. Here the signal is seen for small number of nearest neighbours, $n_v \leq 14$. Since the number of nearest neighbours is small it is useful to study the distribution of the statistic in more detail to rule out possible large deviations from Gaussianity. In Fig. 13 we shown the distribution of S_D for this set with $n_v = 10$. We find that Gaussian provides a good fit to the data. The fit values for 1000 random samples are found to be, mean = 0.2836 and standard deviation = 0.00495. If the number of samples are reduced to 500 we again find a good fit with mean = 0.2834 and standard

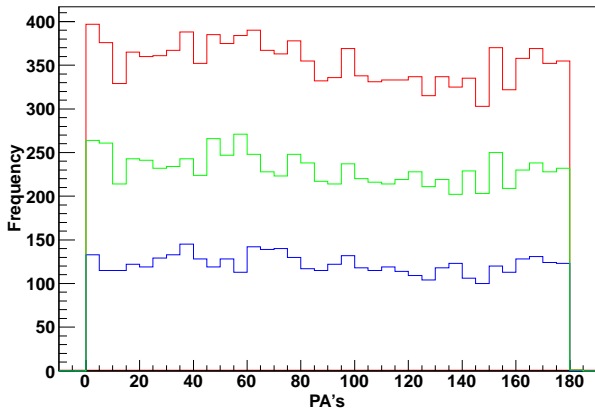


Figure 12. The distribution of polarization position angles (PAs) for the complete data (upper curve) data with polarization flux less than 1 mJy (middle curve) and data with polarization flux greater than 1 mJy (lower curve).

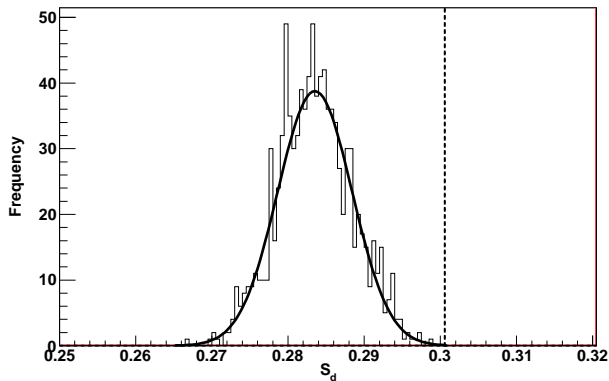


Figure 13. The distribution of statistic S_D for the data with polarization flux greater than 1 mJy and with the number of nearest neighbours 10. The random samples are generated by shuffling the polarization angles among different sources. The Gaussian fit and the statistic for the real data is also shown.

deviation=0.00492. Furthermore in this case we can directly evaluate the significance of the signal by simulations without relying on the Gaussian fit. This determination also agrees well with what is obtained by the significance found by using the fit. Hence the significance we quote in this case is reliable, despite the small number of nearest neighbours.

6 DISCUSSION

The possibility that different sources at high redshift might show correlations at very large distance scales was first indicated by the results of Hutsemékers et al. (1998); Hutsemékers and Lamy (2000). Here it was found that optical polarizations from quasars show alignment over very large distances. The possibility that such sources might indicate a similar alignment at radio frequencies was first investigated in (Joshi et al. 2007). They found that the radio sources do not show any such alignment. Here we test for alignment in radio polarizations using a coordinate invariant statistics. We confirm the results of Joshi et al. (2007) with

the cuts on the polarization flux that they impose. However we do not agree with their conclusions. After imposing the same cut as they impose on the polarization flux we do find a significant signal of alignment for small number of nearest neighbours. The distance scale of alignment here is found to be as large as 150 Mpc. If we do not impose any cut on the data we find a highly significant signal of alignment for a wide range of number of nearest neighbours. The significance is better than 5 sigmas for $150 \leq n_v \leq 350$. This corresponds to a distance scale roughly equal to 500 Mpc. We also find that the sample with low polarization flux, less than 0.5 mJy, shows no alignment. The remaining set with polarization flux greater than 0.5 mJy, however, shows a strong alignment. Similarly we find that sources with degree of polarization less than 0.01 show weak or no alignment. In contrast the sources with degree of polarization greater than 0.01 show a strong signal of alignment.

We also find that the degree of polarization shows a strong negative correlation with the total flux. The data falls into two categories. one of these, which has total flux greater than 100 mJy and degree of polarization between 0.01 and 0.1 shows a random behaviour. The remaining set, however, shows a very strong signal of correlation between degree of polarization and total flux. We find that this second set also shows a very strong signal of polarization alignment, whereas the first set shows no signal.

The signal of alignment we find is similar but may not be identical to that found in (Hutsemékers et al. 1998; Hutsemékers and Lamy 2000) for optical polarizations. There the signal of alignment over cosmologically large distances was found to be significant for large degree of polarization also. In contrast here we find that if we keep only the data with large polarization flux, then alignment is seen only over somewhat smaller distances of order 150 Mpc. However a very strong signal of alignment is seen over much larger distances, of order 500 Mpc, if we do not impose any cut on the polarization flux. Furthermore if we relax the polarization cut slightly to keep sources with polarization flux greater than 0.5 mJy, we again see a strong signal. Similarly sources with large degree of polarization, greater than 1%, show a strong signal, where as the remaining set shows only a weak signal.

We also address the issue of whether the signal might arise due to bias generated by incorrect removal of instrumental polarization. This bias will dominantly affect the sources with low polarizations. Hence if the signal is due to this bias then the signal of alignment should be strongest for low polarizations. However this is not consistent with observations. The low polarization data with polarization flux less than or equal to 0.5 mJy shows no signal of alignment. The data set with degree of polarization less than or equal to 0.01 only shows weak signal for small number of nearest neighbours, n_v , and no signal for larger n_v . Hence it does not appear possible to explain the alignment in terms of instrumental bias. In any case our results provide a strong motivation for testing this signal further with more precise data.

We have not discussed any possible theoretical explanations for the observed alignment. A potential physical effect which could generate such a signal is the large scale correlation in the intergalactic magnetic field (Agarwal, Kamal and Jain 2011; Agarwal et al. 2012). If

the intergalactic magnetic field has a primordial origin (Subramanian and Seshadri 2003), then it could show correlations over very large distance scales. Such large scale correlations could generate the observed alignment by either affecting the electromagnetic radiation during propagation through intergalactic medium or by intrinsically aligning the sources at high redshift. One possible way in which the background magnetic field may affect the radiation propagating over cosmological distances is by mixing with hypothetical pseudoscalar particles (Agarwal, Kamal and Jain 2011; Agarwal et al. 2012). Pseudoscalar-photon mixing leads to very small polarizations at radio frequencies in contrast to optical frequencies. Hence the absence of large distance correlations we found at radio frequencies for large polarization flux may be consistent with the predictions of this effect. This requires a detailed study which we postpone to future research.

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